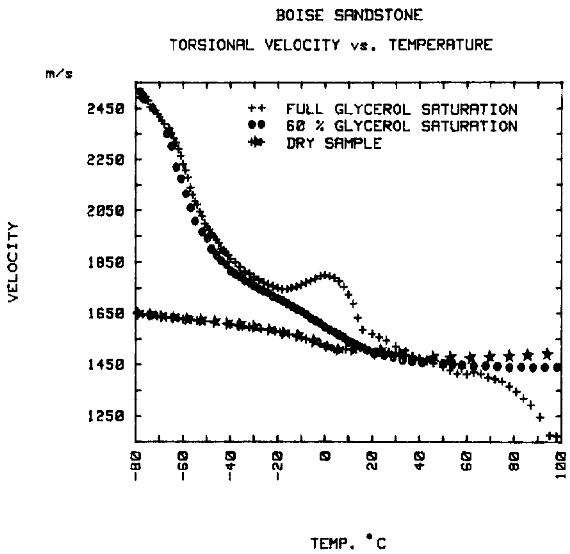

FIG. 5. Wave velocities in Boise sandstone samples containing air, air/glycerol, and glycerol in the pores.

Conclusions

The experimental results are as yet insufficient to resolve the detailed mechanisms responsible for the complex dependence of velocities and Q^{-1} on temperature in viscous liquids and liquid saturated rock. However, our data show that the fluid rheology strongly affects both wave velocity and attenuation in viscous liquids as well as rocks saturated with these liquids. The results of the sonic experiments suggest that (1) the attenuation peaks in liquid saturated rock are associated with relaxation processes in the liquid itself; (2) these peaks occur at higher temperature in the rock than in the fluid itself; (3) amplitude of the Q^{-1} peaks is greater in the rock than in the fluid itself; and (4) velocity in saturated rock decreases with decreasing pore fluid viscosity much more than in the fluid itself.

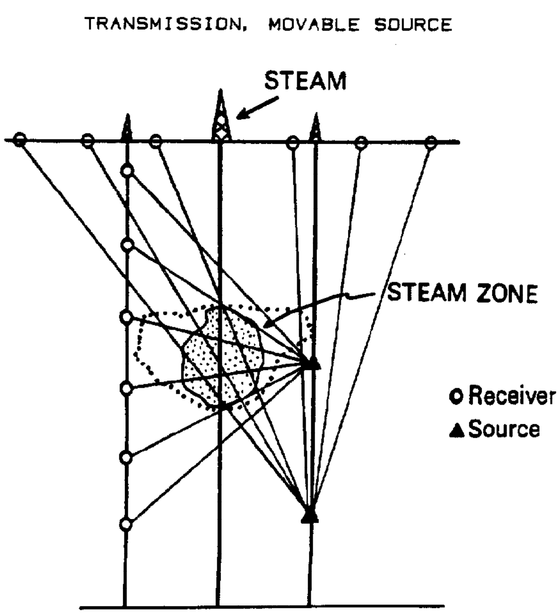

FIG. 6. Possible applications of the results to the monitoring of thermal EOR via seismic imaging.

Furthermore, ultrasonic studies show the following. (1) Tar and heavy-oil sands containing a percentage of oil in the pores have strongly temperature-dependent seismic velocities and amplitudes. Neither brine nor gas-saturated samples display this behavior. (2) The magnitudes of the dependence of compressional velocities and amplitudes on temperature are proportional to the oil content of the sample. (3) Large changes in compressional velocities and amplitudes were measured when steam was generated in the pore space of a brine-saturated sand. Sands that were saturated with oil or with a mixture of half brine and half oil showed no detectable changes in seismic properties through the steam transition.

The very large magnitudes of the effects of temperature and steam on the measured seismic properties of laboratory samples strongly suggest that efforts to monitor thermal EOR fronts, including hot water and steam floods (Nur, 1982), should be highly successful if seismic signal strength and spatial resolution can be made adequate (Figure 6). In addition, the velocity and amplitude measurements in reservoir sands such as reported here indicate that seismic properties can be used as a thermometer to map the spatial distribution of heated oil within reservoirs.

Acknowledgments

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Low-Frequency Electromagnetic Logging RS7

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Controlled-source electromagnetic sounding (CSEM) is becoming a valuable tool for resolving certain geologic features in problem areas where seismic reflection methods are unsatisfactory. The detection of electrically conductive sediments beneath overthrust sections of older rock or beneath volcanic flows are examples of such situations. Another type of sounding can be made if a drill hole is available in the area. In this case, the transmitter is located on the surface and the receiver is lowered down the hole. The advantage of surface-to-borehole sounding is that the method is inherently more sensitive to subsurface layering or inhomogeneities than surface-only measurements. A surface-to-downhole EM technique for petroleum exploration would also have inherent advantages over conventional well logs for determining subsurface conditions away from or below the well. In particular, it may also be possible to determine these conductivities in the presence of the casing.

A preliminary analysis shows that there is no surface dat that could resolve the layering as well as in the in-hole quadrature data. It should also be noted that no surface data even approach the resolution provided by high-frequency field measurements taken across the interface at depth. Further, standard in-hole tools have a relatively small radius of investigation away from the hole. The sounding experiment on the other hand responds to integrated conductivities out to radii on the order of the depth of the sensor. Clearly, different volumes are sampled and the difference in interpreted conductivity could reveal differences in micro- and macrofracture porosity as well as the radial extent of porous horizons measured in the hole. Such measurements could be useful in determining the effective increase in porosity and/or permeability associated with hydrofracturing. To study the effects of the casing we formulated the problem of a circular current loop coaxial with a cylindrical shell (casing) in a conducting whole space. The fields are calculated on the axis, within the casing, as a function of frequency of the alternating current in the loop. The model is idealized since, in practice, the loop lies on a half-space, but for receivers distant from the loop it is unlikely that the results are affected by this whole space representation. This study showed that the formation response is of the same order as the casing response in a frequency window from 0.5 to 20 Hz. The change in response for a change in formation resistivity at a constant frequency is a measure of the sensitivity of the technique for determining formation resistivity. In the range of 1.0 to 10.0 $\Omega \cdot$ m, the important range for sedimentary rock studies, the sensitivity is very good.

Controlled-source electromagnetic sounding (CSEM) is becoming a valuable tool for resolving certain geologic features in problem areas where seismic reflection methods are unsatisfactory. The detection of electrically conductive sediments beneath overthrust sections of older rock or beneath volcanic flows are examples of such situations. Typically, the transmitters and receivers are located on the surface and the observed EM responses, in either time or frequency domain, and as a function of array geometry are used to infer the conductivity distribution at depth. Examples of such surveys using a horizontal loop source developed by Lawrence Berkeley Laboratory and Engineering Geoscience were given by Wilt et al. (1983). Examples of data taken with a grounded wire source were given by Keller et al. (1983). To date, most of the published cases deal with mineral and geothermal exploration.

Another type of sounding can be made if a drill hole is available in the area. In this case, the transmitter is located on the surface and the receiver is lowered down the hole. The advantage of surface-to-borehole sounding is that the method is inherently more sensitive to subsurface layering or inhomogeneities than surface-only measurements. Surface-to-downhole EM measurements have not yet been reported for petroleum exploration, although VSP is a seismic example of a seismic surface-to-borehole technique that is frequently used. A surface-to-downhole EM technique for petroleum exploration would also have inherent advantages over surface measurement and conventional well logs for determining subsurface conditions away from or below the well. In particular, it may also be possible to determine these conductivities in the presence of the casing.

Discussion of the technique

To illustrate the technique we assume that a drill hole penetrates an arbitrarily layered earth to some depth. A horizontal EM transmitter loop is coaxial with the hole and will energize the earth by means of a broadband EM signal. A suitable magnetic field detector measures the resultant field within the well. Despite the potential usefulness of this arrangement for increasing the resolution of layered model parameters or for increasing the sensitivity of soundings to structure or layering below the drill hole, we do not have as yet a numerical solution for the general case of an n-layered earth. However, to illustrate the methodology and its advantages, we have rewritten and exercised a program that calculates the vertical fields in a two-layer earth along the axis of a borehole concentric with the loop. This program could be generalized to give the magnetic and electric response in any layer of a multilayer model and at any radial distance from the axis of the loop.

The purpose of the calculations performed were to show that the in-hole fields are indeed sensitive to boundaries between layers of different conductivity when the receiver passes through them. This property relates to how well the conductivity could be measured as a function of depth, and thus to the question of resistivity logging in cased wells. Preliminary calculations suggest that the conductivity may be measured through the casing at low frequencies. The sample model used here is energized by a horizontal loop with 200 m radius (moment M is thus equal to $4\pi I \times 10^4$, where I is the current). The fields were calculated in the frequency domain in the borehole and along the surface. The fields are in units of gammas for a transmitter moment of unity. Practical values are simply obtained by multiplying calculated results by the actual transmitter moment. The fields are calculated first for a infinite half-space whose resistivity is that of the upper layer ρ_1 (100 $\Omega \cdot$ m and then for the two-layer (conductive basement ρ_2, of 1 $\Omega \cdot$ m at 1.0 km). The response curves for each are identified by the $\rho_1 : \rho_2$ values. The fields were not normalized by the primary, free-space field.

In general, the resolution of layer parameters depends on how a particular magnetic field component changes for a change in parameters. Thus, for detecting a basement conductor, the field component that undergoes the largest change in value when the conductor is brought into the half-space is best quantity to use. This same criterion is used to choose the best transmitter-receiver geometry. The actual field values and their differences, rather than ratios, would be employed in this evaluation since there are practical noise limits in the actual measurements. For example, the half-space and two-layer models might produce a field ratio that is huge at some low frequency, but the low signal strength that might occur in practice could be below the detection level of the sensor.

Figure 1 shows the real and quadrature (imaginary) parts of H_z as a function of depth at frequencies of 1, 10, and 100 Hz. Real H_z is dominated by the primary field and the only significant differences in the two models occur very close to the interface. At 100 Hz the skin depth is 500 m in the first layer, so the conductor is difficult to detect until one is virtually at or within it. There would be little difficulty in accurately locating the interface, however, should the borehole penetrate it. The quadrature field falls off much more slowly but still shows the conductor as the interface is

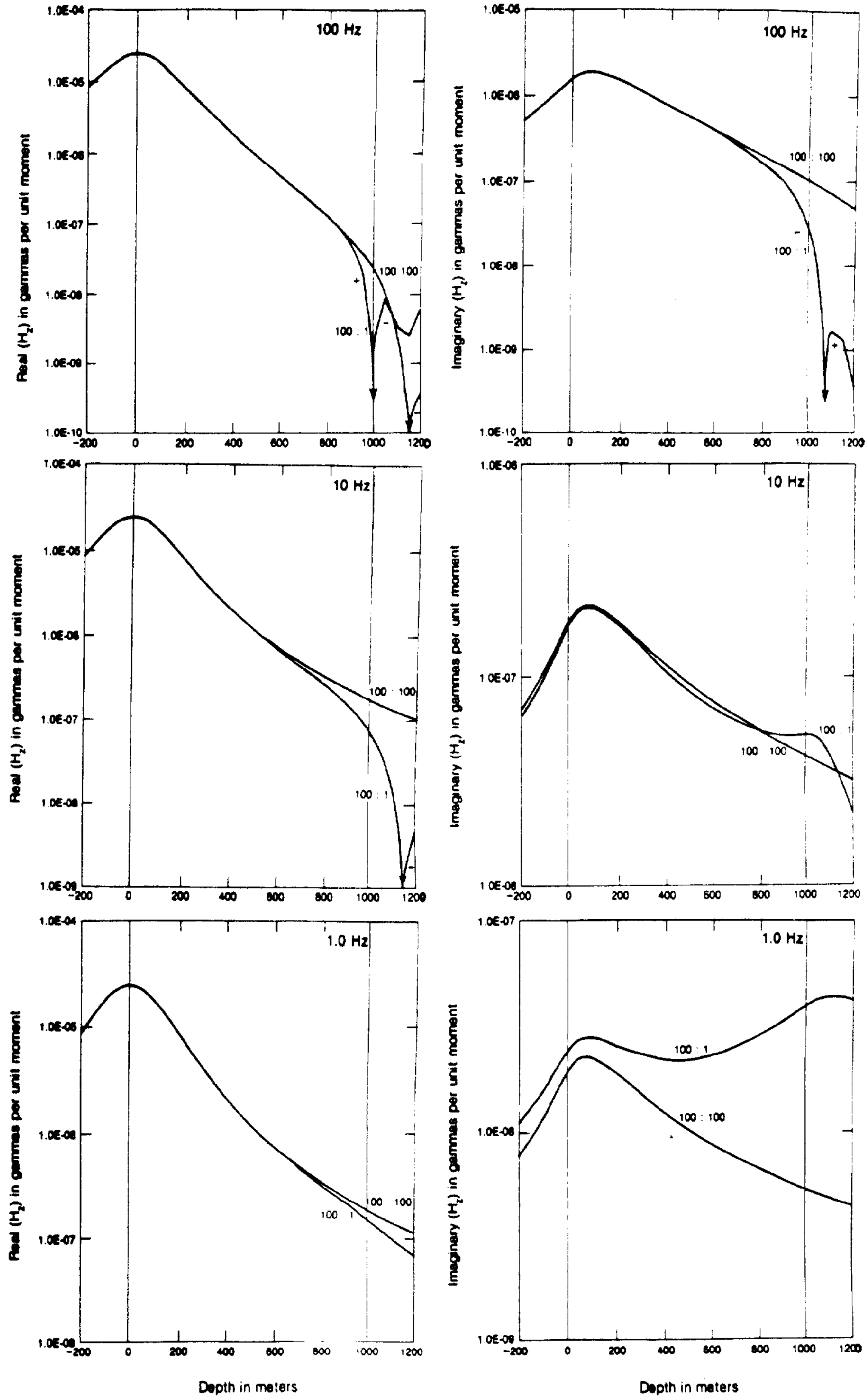

FIG. 1. Real and quadrature parts of H_z as a function of position in drill hole for the half-space model ($\rho_1:\rho_2$ = 100:100) and the 2-layer model ($\rho_1:\rho_2$ = 100:1).

penetrated. At 10 Hz the real component again sharply defines the interface, but the quadrature field is in a transition stage having values less than the half-space response to much greater than the half-space. At 1.0 Hz there is a dramatic difference between the two models in the quadrature component and the difference increases with depth. The conductor is well detected anywhere in the hole but the position of the interface, given as the receiver moves

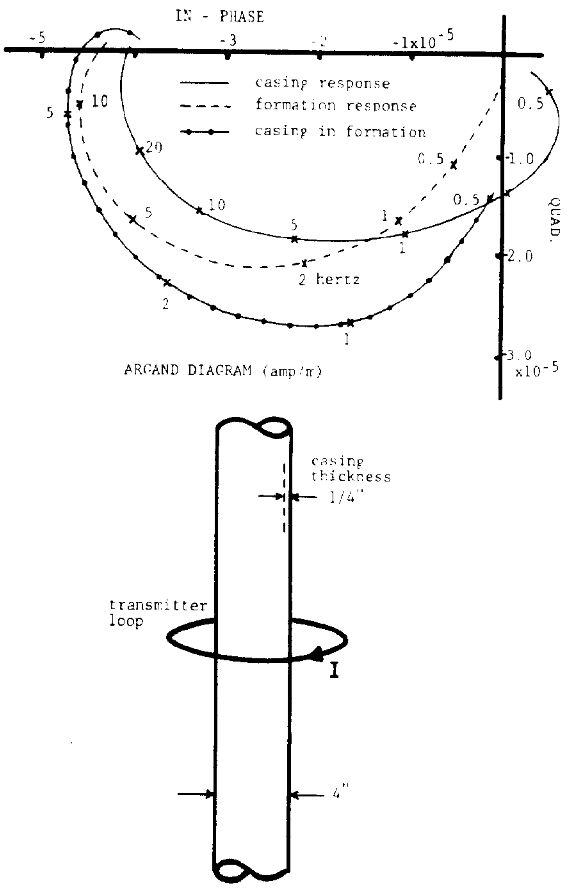

FIG. 2. Argand plot of the response of a receiver in the casing in free space, in the formation, and with casing in the formation. Casing and transmitter in the whole space.

through it, might be less precise due to the lower resolving power of the low-frequency EM wave.

In summary, high-frequency data serve to locate accurately the interface, and presumably measure the conductivity contrast, if the sensor passes through it. To infer the depth of the interface from a position in the hole above it, low frequency values of the quadrature component at any point are satisfactory. The difference between the two models increases with depth showing that the conductor is better resolved the closer the receiver approaches it.

An important question at this point is whether or not measurements made on the surface at various distances from the transmitter could resolve the conductor just as well as measurements made in the hole. To illustrate this situation we calculated fields on the surface with different offsets from the transmitter as a function of frequency. These fields were then compared with those computed in the borehole for their amplitudes and amplitude differences. As one might expect there are strong patterns in the response curves at different offsets that indicate that the layering could indeed be well resolved with the surface data, but in every case the field strength of the data in the hole is greater and the maximum difference between models is often an order of magnitude greater for the in-hole data.

From these preliminary analyses we conclude that there is no surface data that could resolve the layering as well as the in-hole quadrature data. Further, it should be noted that no surface data even approach the resolution provided by high-frequency field measurements taken across the interface at depth.

One of the problems associated with borehole sounding is to identify the effects of the casing on the measurement. To study this we formulated the problem of a circular current loop coaxial with a cylindrical shell (casing) in a conducting whole space, Figure 2. The conductivity and the relative permeability of the casing material used is 10^6 mhos/m and 10^3, respectively. The fields are calculated on the axis, within the casing, as a function of frequency of the alternating current in the loop. The loop radius used is 100 m. The model is idealized since, in practice, the loop lies on a half-space but for receivers distant from the loop it is unlikely that the results are affected by this whole space representation.

Figure 2 shows a standard Argand plot of the in-phase and quadrature secondary fields measured at a point 500 m below the loop transmitter as a function of frequency. The response inside the casing alone (in free space), in an uncased hole in a formation of 1 $\Omega \cdot$ m resistivity, and in a cased hole in the same formation are all shown on the same plot. From this plot it is evident that the formation response is of the same order as the casing response in a frequency window from 0.5 to 20 Hz. The change in response for a change in formation resistivity at a constant frequency is a measure of the sensitivity of the technique for determining formation resistivity. In the range of 1.0 to 10.0 $\Omega \cdot$ m, the important range for sedimentary rock studies, the sensitivity is found very good in our preliminary study.

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